The temporal variability of mesoscale eddies:

Understanding the drivers and predictability of oceanic "storms"

Andrew Delman (329B), Tong Lee (329B), Bo Qiu (U. of Hawaiʻi, Mānoa)

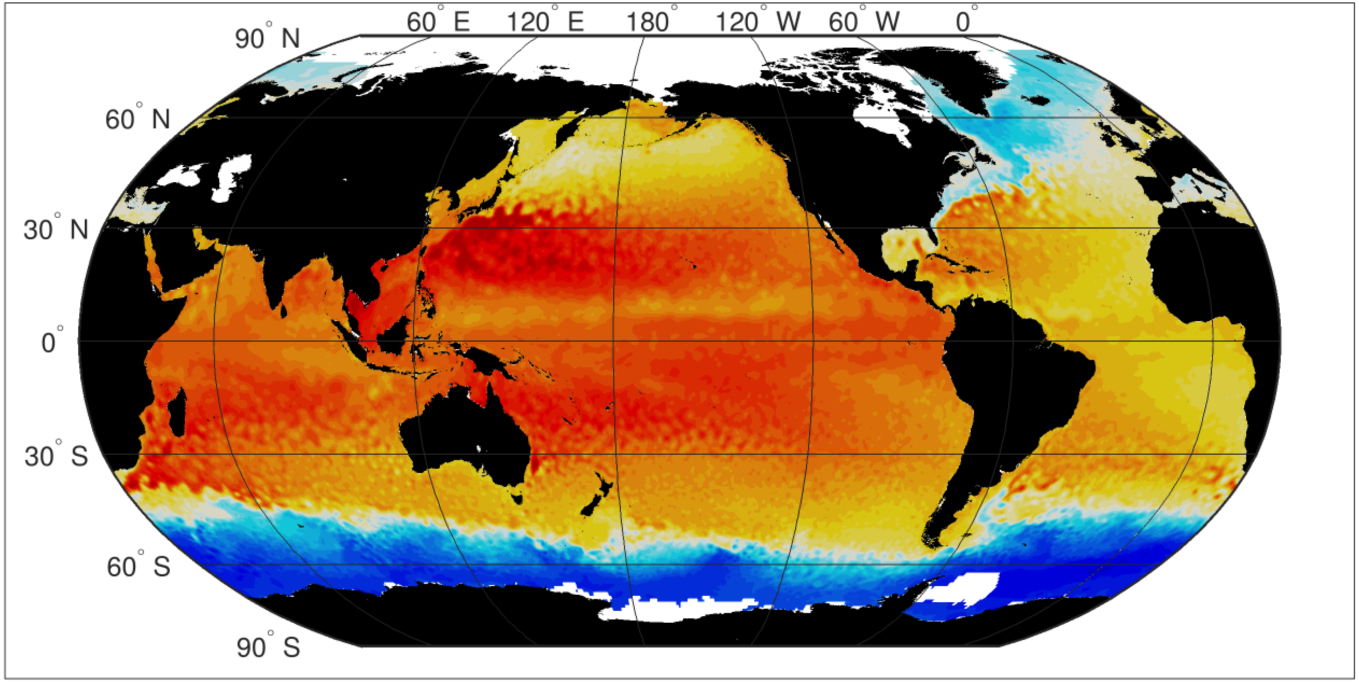

Image: Absolute dynamic topography on 1998 Jan 01, from SSALTO/DUACS

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JPL Postdoc Seminar Series

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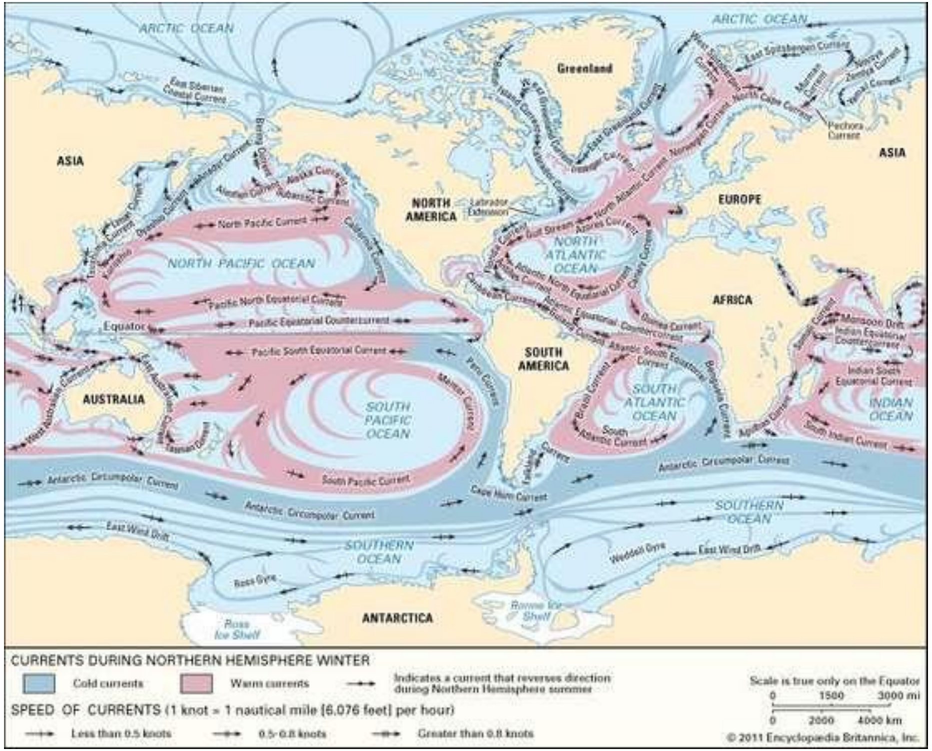
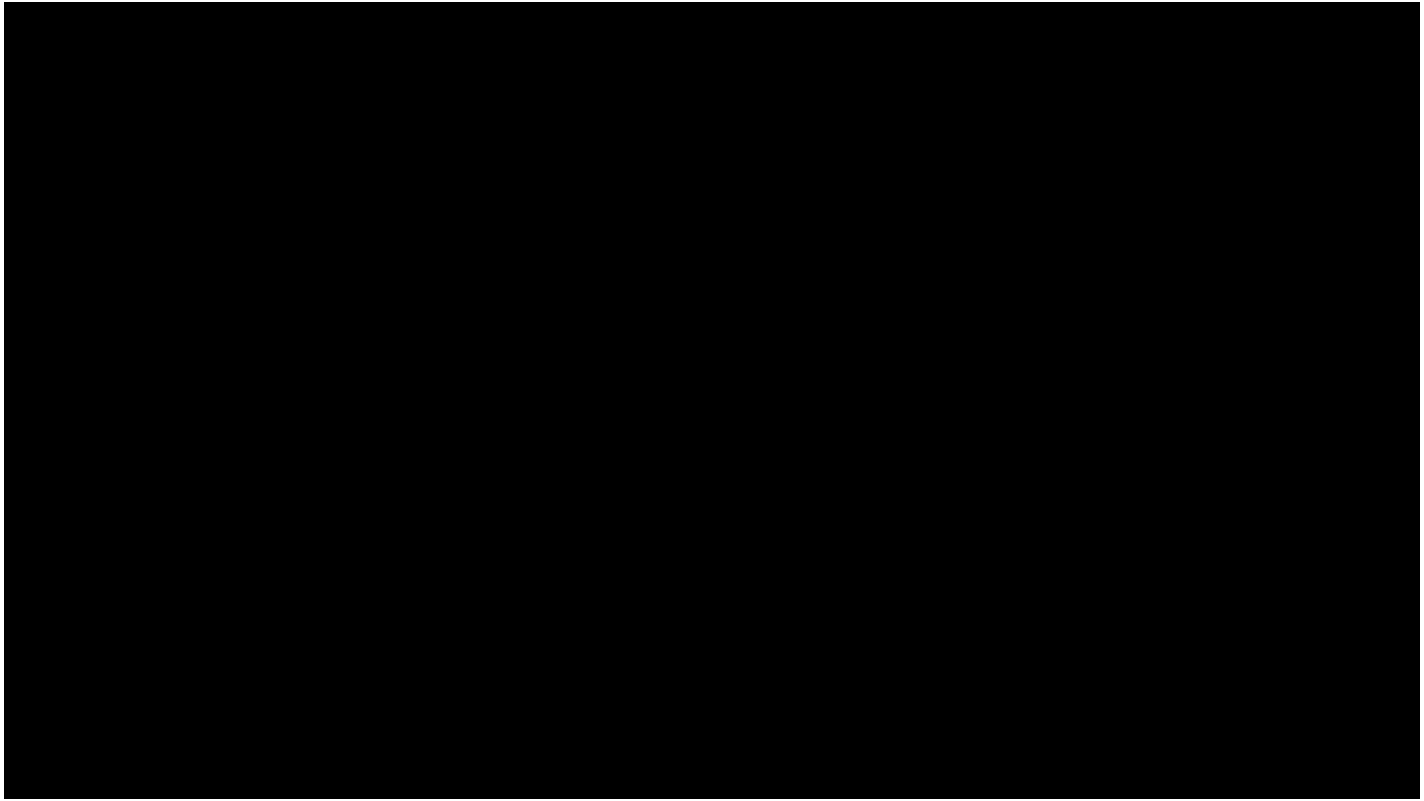
A “traditional” view of the ocean circulation

(through most of the 20th century)



Source: Encyclopædia Britannica

Then came Seasat, Geosat, and in 1992, TOPEX/POSEIDON…

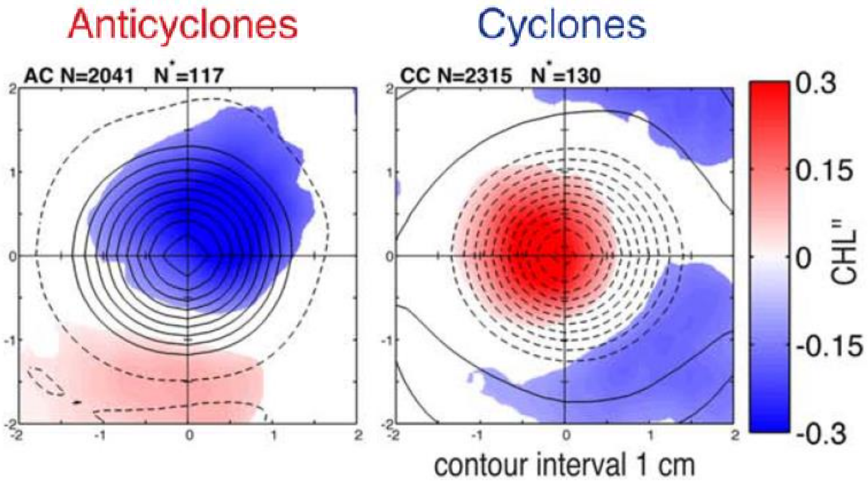


Source: Peter Gaube lab (APL-UW), YouTube (https://www.youtube.com/watch?v=pChhyK0pwhI)

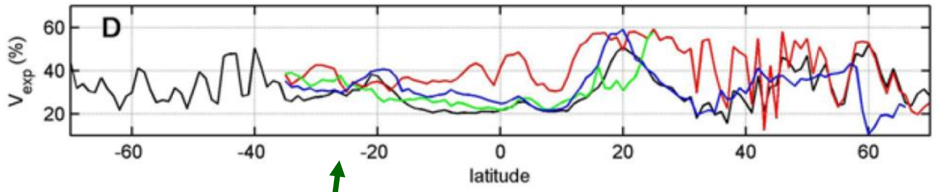
Impact of eddies on the ocean

- Nutrients are accumulated in the interior of some eddies, supporting chlorophyll blooms
- Transports heat (and salt, and momentum, etc.) – v'T', v'S', v'v'

Composite chlorophyll anomalies inside mesoscale eddies – California Current
Gaube et al. (2014)



% of total heat transport variance explained by eddy heat transport
Volkov et al. (2008)



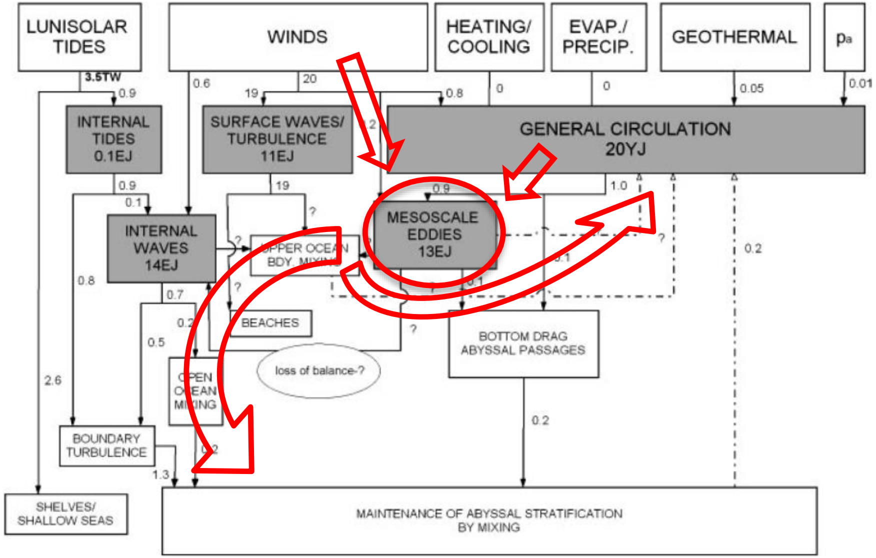
Mesoscale eddy heat transport explains 20-60% of total heat transport variance

Impact of eddies on the ocean

- Nutrients are accumulated in the interior of some eddies, supporting chlorophyll blooms
- Transports heat (and salt, and momentum, etc.) – v'T', v'S', v'v'
- Energy transfer between large and small scales

Rough schematic energy budget of the global ocean

Wunsch and Ferrari (2004)



Large-scale

Small-scale

A measure of eddy strength

Eddy kinetic energy (EKE)

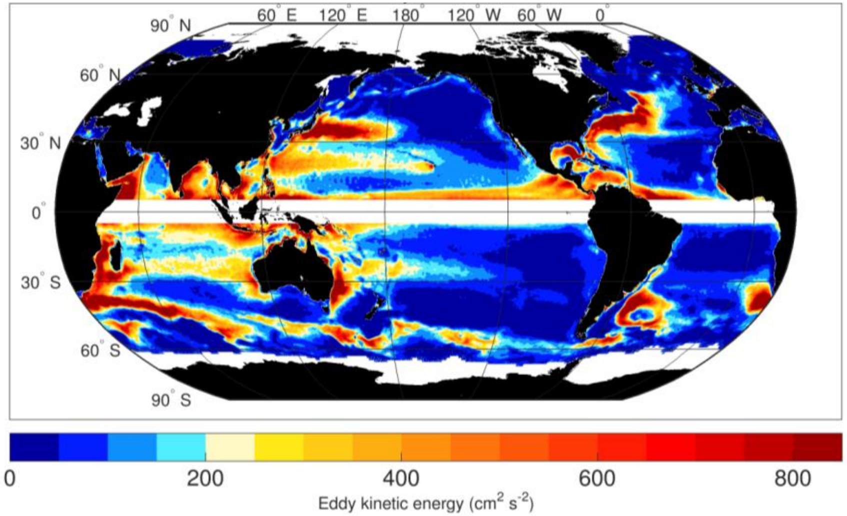
$$EKE = 0.5*[(u')^2 + (v')^2]$$

- u' and v' are the components of the velocity vector, with the time-mean velocity removed

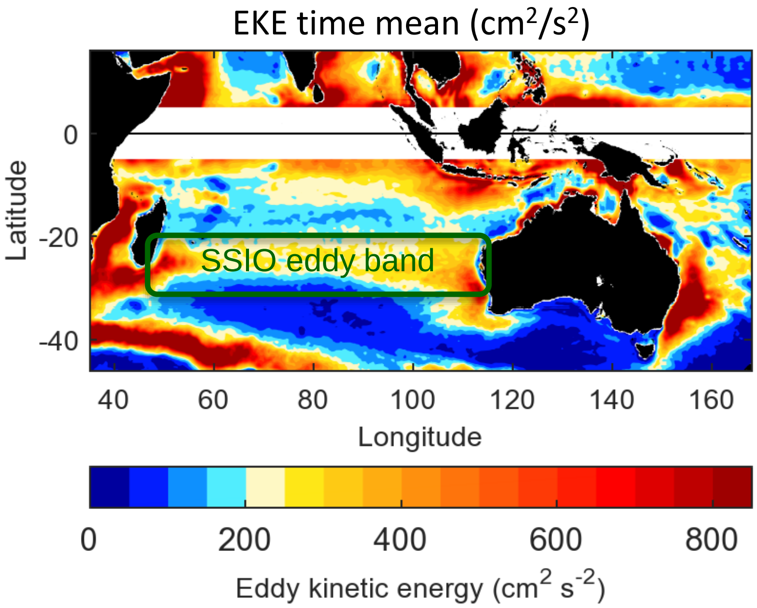
Altimetry missions:
TOPEX/POSEIDON
ERS-1
Jason-1
ERS-2
OSTM/Jason-2
ENVISAT
Jason-3
SARAL/AltiKa
Cryosat-2
Sentinel-3A
HY-2A

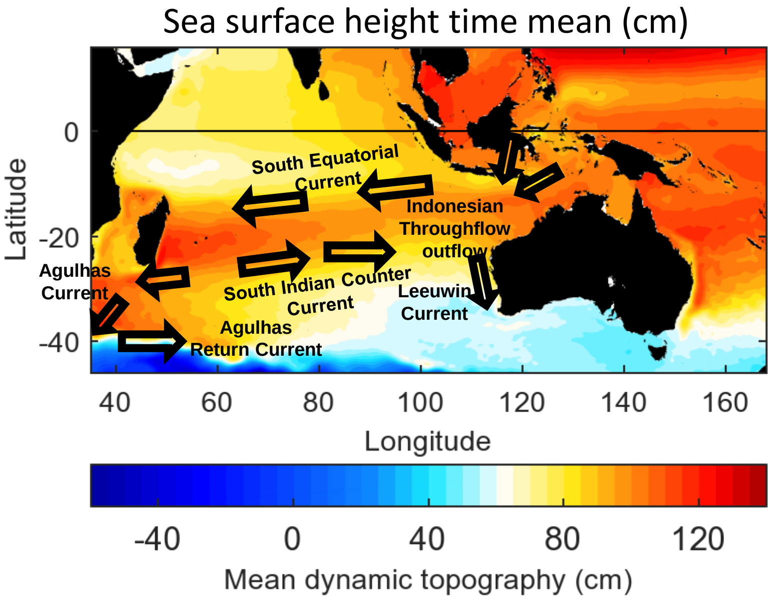
SSALTO/DUACS:
- merged multi-mission gridded altimetry dataset
- daily, 1/4° resolution
- 24+ years of record (1993-2017)

Time-mean EKE, from gridded altimetry data (SSALTO/DUACS)



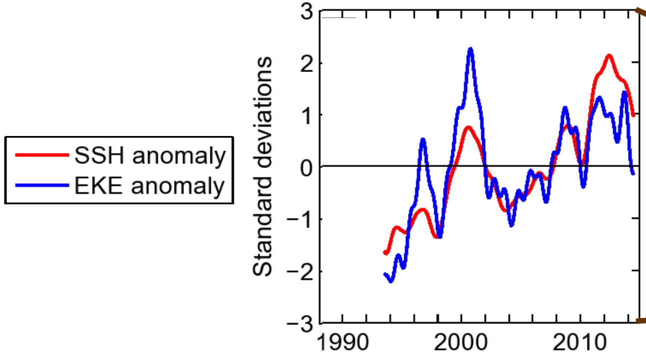
The Subtropical Southern Indian Ocean (SSIO) and eddy variability



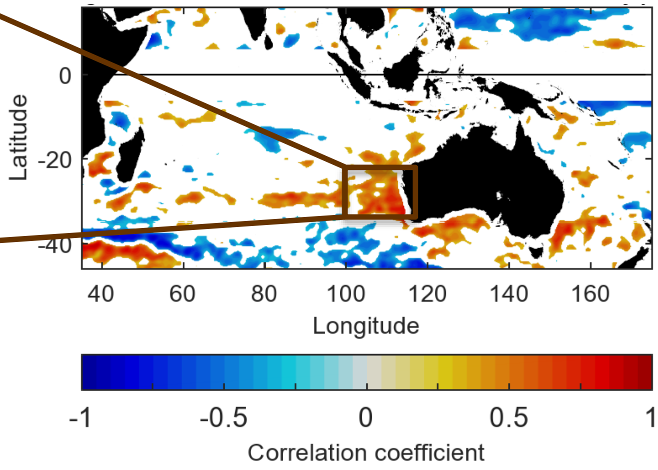


Subtropical Southern Indian Ocean EKE and sea level variability

SSH and EKE anomalies from altimetry,
averaged in the Leeuwin Current west of Australia



SSH-EKE anomaly correlation (after detrending), 0 lag



SSH and EKE anomalies are correlated in the eastern SSIO (Leeuwin Current region)

Research questions – SSIO eddy variability

Given we know that…

- Mesoscale eddies are major contributors to ocean heat/salt transport, energy transfer between scales, and biological productivity

- SSIO eddies may be influenced by sea level variations locally and in the Pacific

We seek the answers to these research questions:

- **Which mechanism(s) explain the close relationship between SSH and EKE on interannual/decadal timescales in parts of the SSIO?**

  …with possible implications for long-term trends in SSH & EKE

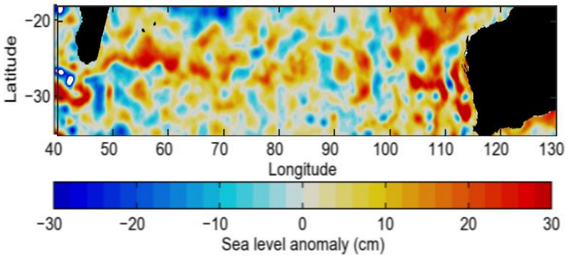
- **Which climate and/or interior ocean forcings control the interannual variability of EKE in the SSIO?**

  …with possible implications for heat/tracer transport variability & predictability

Separation of oceanic motions by spatial scales

In order to focus on dynamics at mesoscales (tens of km to ~200 km), we define a measure of EKE that distinguishes between mesoscale and large-scale motions in the ocean:

- Low-pass filter SSH (or SLA with the time mean removed) in both x and y
- Use 6° wavelengths (~670 km) as the cutoff threshold



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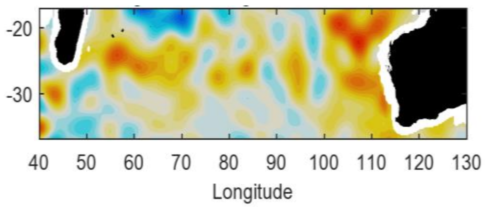

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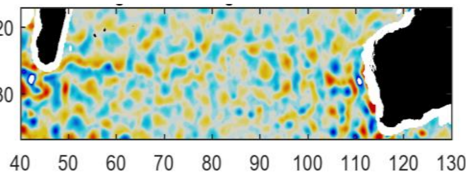


AVISO SLA snapshot 2011 Jul 02

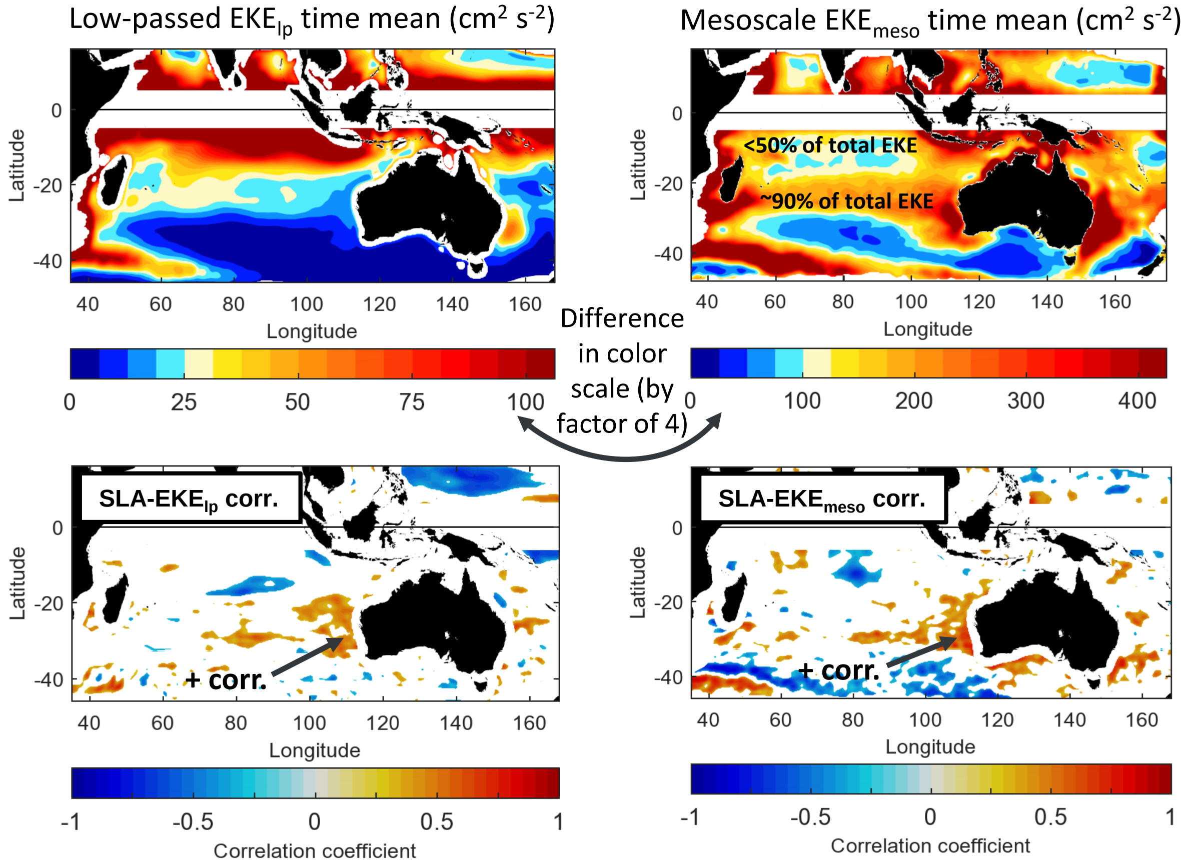
$\mathrm{SLA}_{\mathrm{lp}}$

$\mathrm{SLA}_{\mathrm{meso}}$

- The low-passed field represents larger-scale motions
- Residual represents mesoscale motions (such as eddies)
- EKE can be computed from each individual field, e.g.,

$$\mathrm{EKE}_{\mathrm{meso}} = \frac{1}{2}\left\|\hat{\mathbf{k}} \times \frac{g}{f}\nabla(\mathrm{SLA}_{\mathrm{meso}})\right\|^2$$

Distribution of EKE associated with large scales and mesoscales



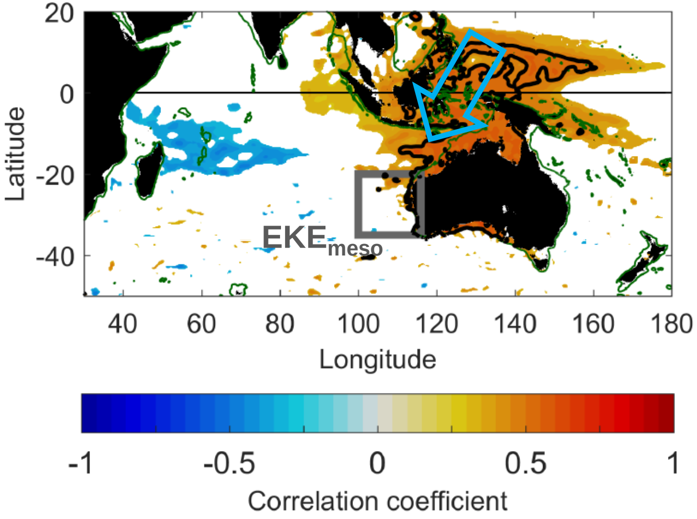
- Robust positive correlation between SLA and EKE at all scales, **but mostly in eastern SSIO**

Hypothesis: Pacific forcing influences both SSH and EKE variations, instead of SSH forcing EKE

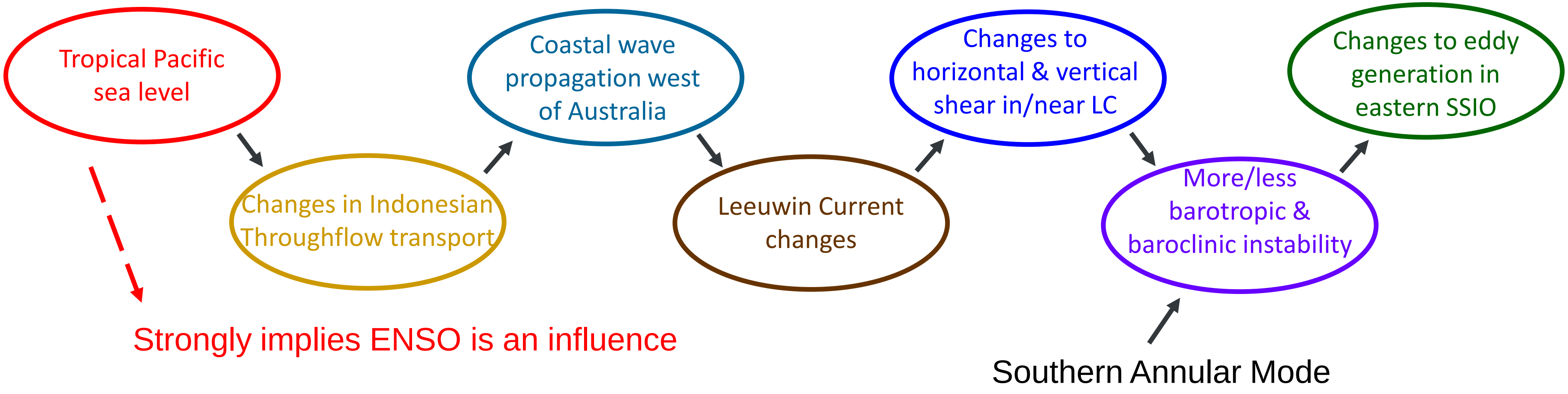
- The correlation of SLA in the tropical Pacific leading mesoscale EKE in the eastern SSIO implies that Pacific dynamics are an important influence on SSIO eddy activity

Correlation of SLA leading box-averaged EKE_{meso}

6 month lead time



Possible mechanisms for Pacific influence on eastern SSIO eddy activity:



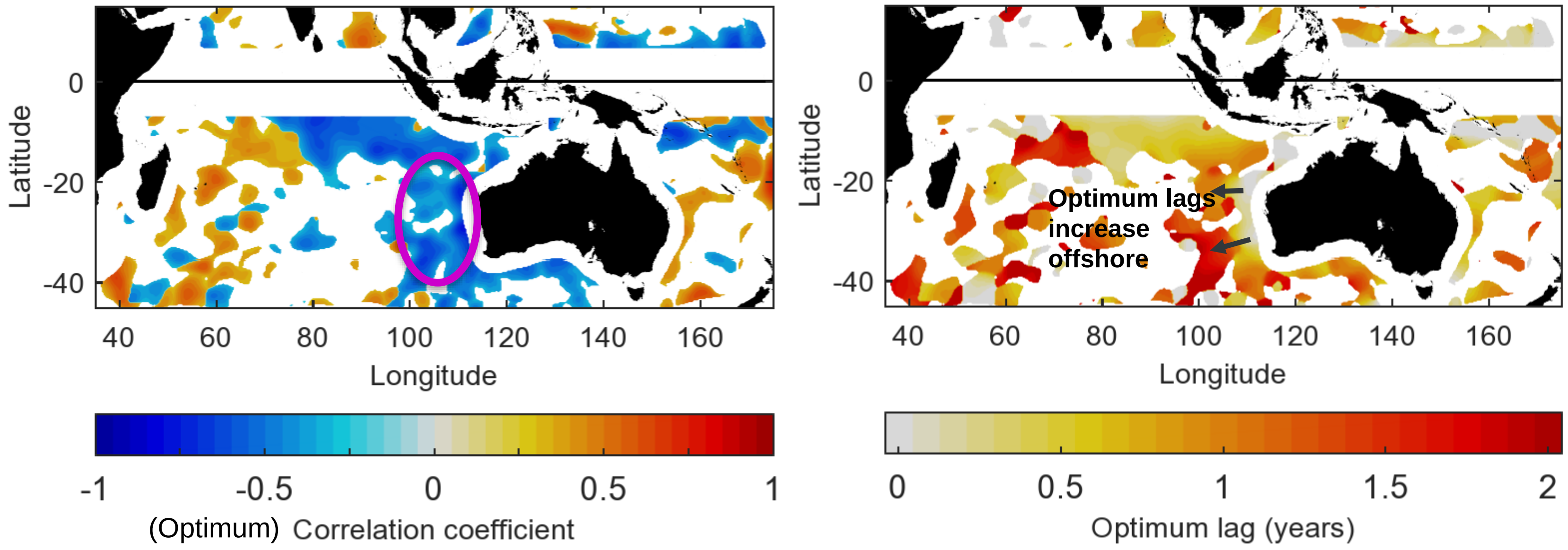
- Jia et al. (2011) found a significant correlation with the Niño3.4 index, which was not further explored in that study

- They did attribute SSIO EKE variability to wind stress curl changes related to the Southern Annular Mode (SAM)

Optimum correlations of Niño3.4 index leading mesoscale EKE

What is an "optimum" correlation?

- Correlate the time variation of a single index with the time variation in regional maps of another quantity
  - Plot the maximum magnitude correlation coefficient and its associated lag



Optimum correlations of Niño3.4 index leading mesoscale EKE

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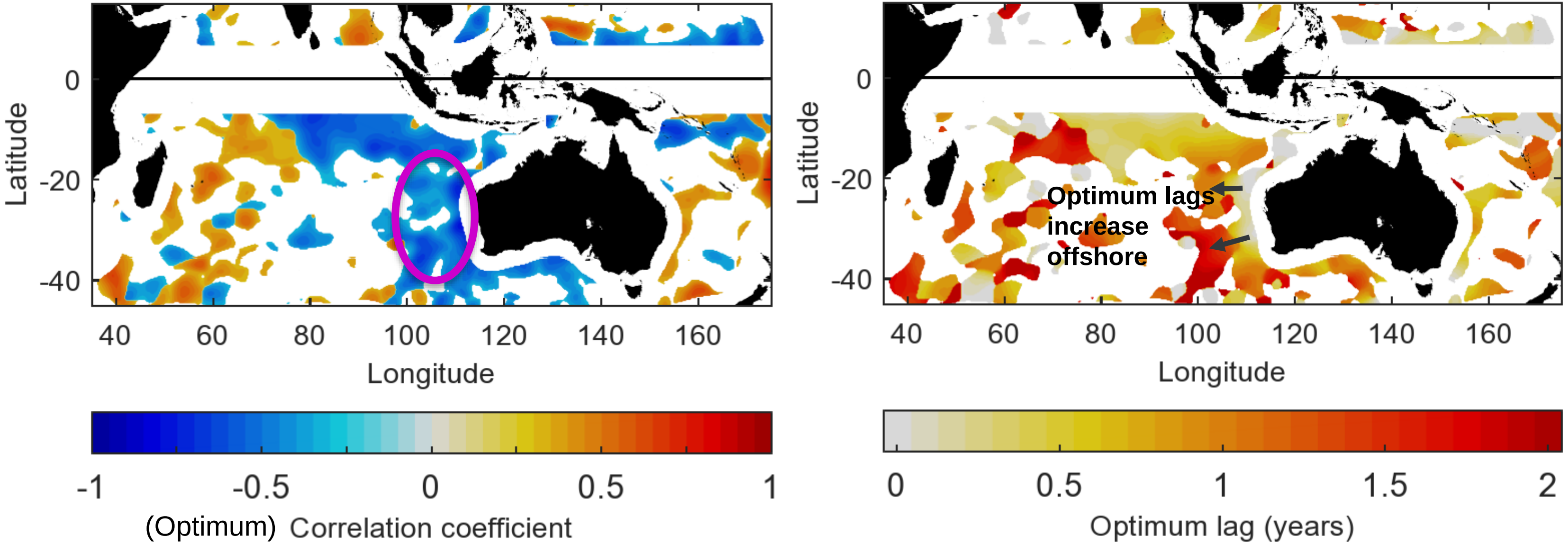
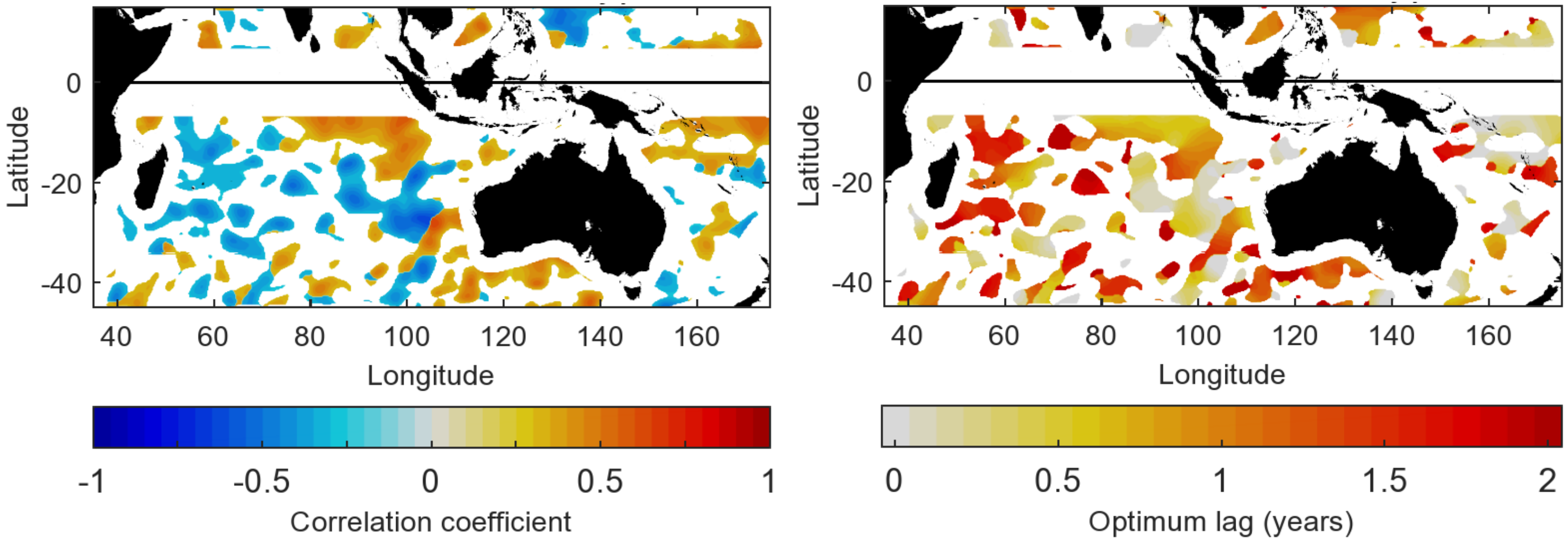


- Results: Optimum correlation is robustly negative east of 100°E; mostly insignificant elsewhere
  - El Niño → lower mesoscale EKE near Australia
  - La Niña → higher mesoscale EKE near Australia
- Lag of EKE_{meso} relative to Niño3.4: several months near the coast; >1 year further offshore

Optimum correlations of Southern Annular Mode (SAM) index leading mesoscale EKE



- Generally negative correlations with EKE_{meso} in the SSIO band, but only significant in scattered regions
  - According to Jia et al. (2011), mechanism for SAM influence is related to wind stress curl just west of Australia, so this may not be influential in the rest of the SSIO
    (Optimum)
- Optimum lags do not show clear spatial progressions

So we have established:

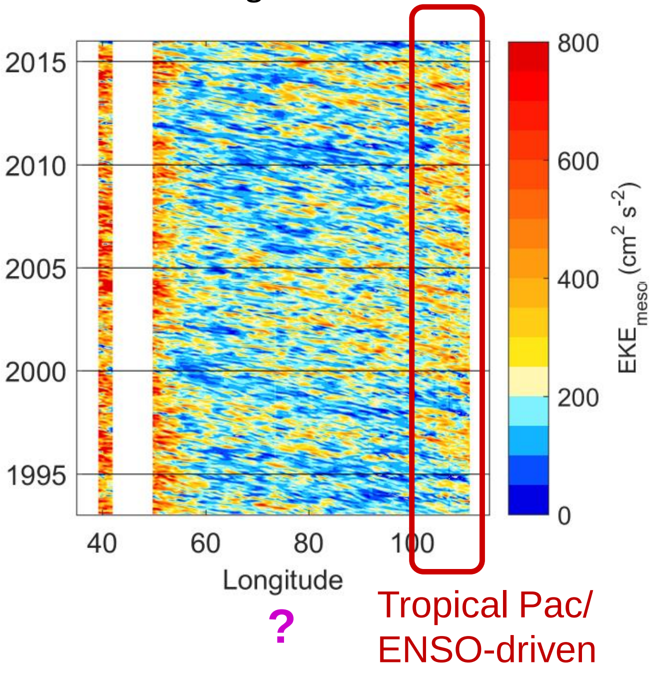
- ✓ **That the SLA-mesoscale EKE relationship in the eastern SSIO (near Australia) appears to be related to Pacific forcing**
  - → Pacific forcing influences both SSIO sea level anomalies and SSIO EKE variations **(confirmation of hypothesis)**

- ✓ **That ENSO has a strong influence on levels of mesoscale eddy activity in the eastern SSIO**
  - → El Niño leads to a weaker Leeuwin Current and less eddy generation
  - → La Niña drives a stronger Leeuwin Current and more eddy generation

But we have not established:

- ? **The mechanism(s) responsible for explaining substantial EKE variability in the central and western SSIO**

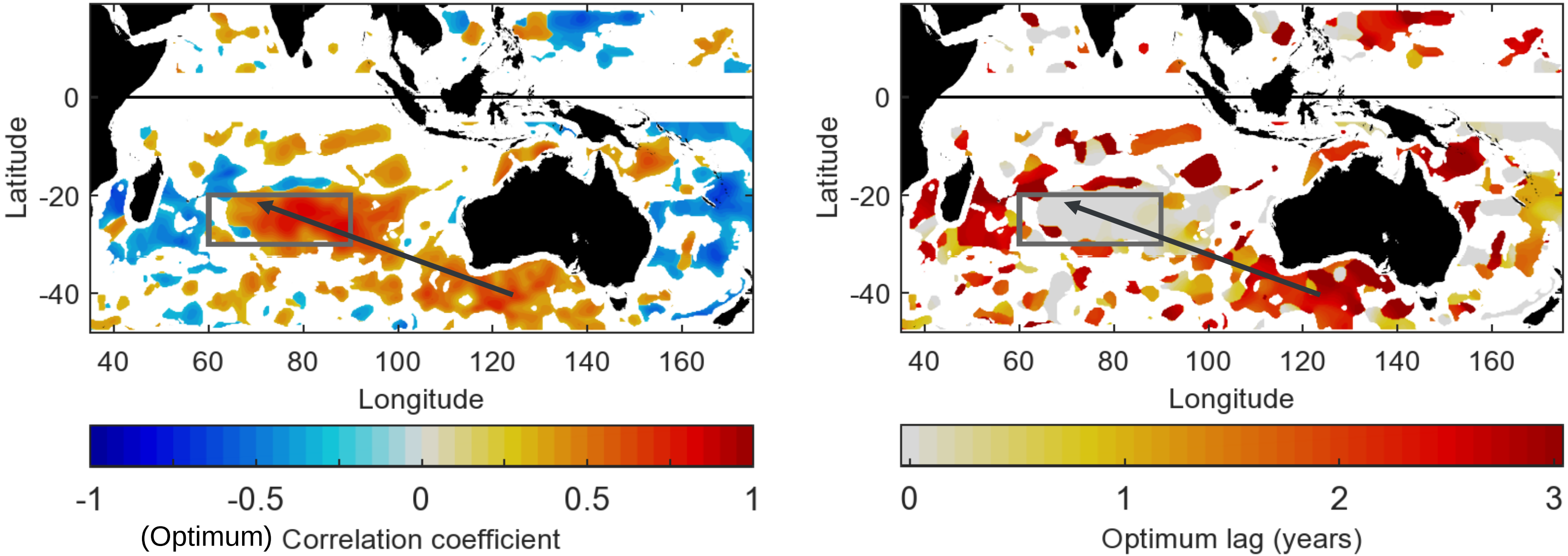
Hovmöller diagram of mesoscale EKE, averaged 25°-20° S



What controls mesoscale EKE variability in the central/western SSIO?

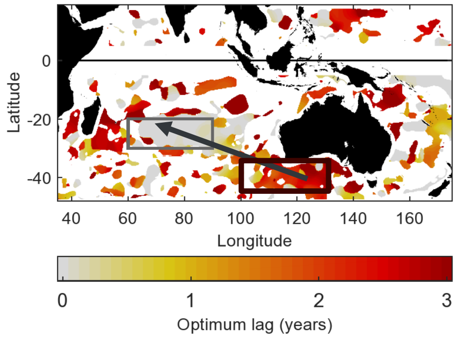
- Optimum correlate EKE_{meso} with itself
  - Average EKE_{meso} in a box in the central/western SSIO, and lag correlate with (point) EKE_{meso} values
- Objective: look to see if eddy energy propagation (internal to the ocean) is implied by the lagged correlations

Optimum correlations and lags, of regional EKE_{meso} leading box-averaged EKE_{meso}

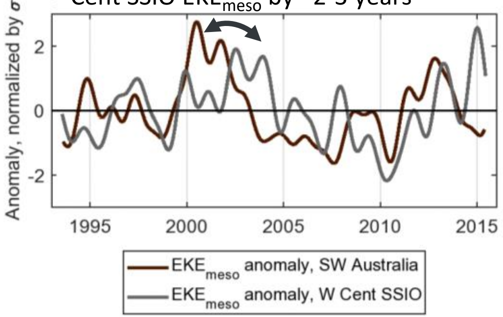


- Apparent propagation of eddy energy from southeast to northwest, with lags of up to 3 years

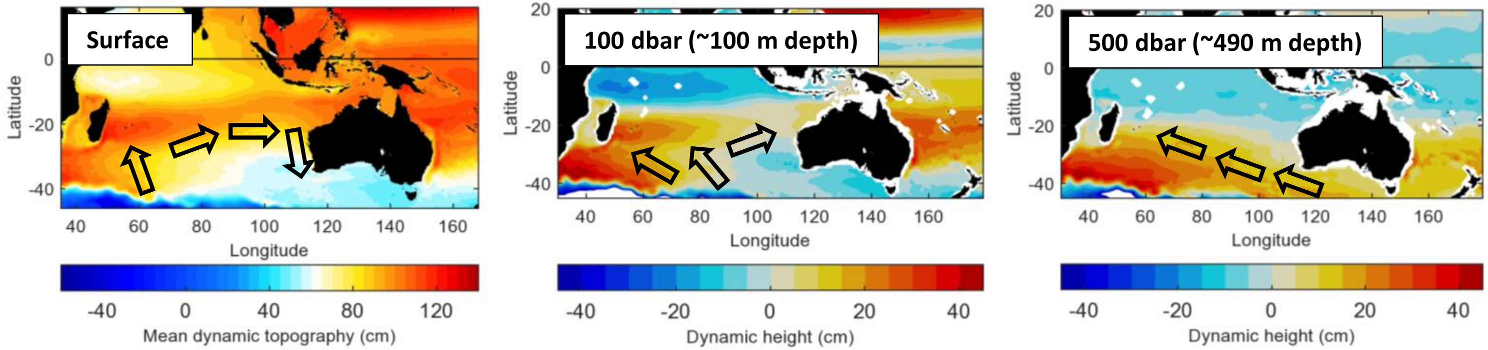
- Mesoscale eddies generally propagate westward, with slight north/south deflections depending on their sign (cyclonic or anti-cyclonic)
- So could there be net mesoscale energy propagation towards the northwest in this region?



SW Australia EKE_{meso} leads W Cent SSIO EKE_{meso} by ~2-3 years



Mean large-scale circulation in the region (from World Ocean Atlas 2013 v2 data)

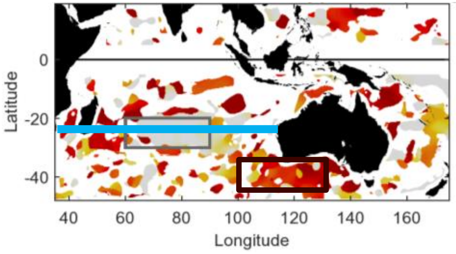


Flow at surface is not favorable for NW propagation… but flow beneath the thermocline certainly is

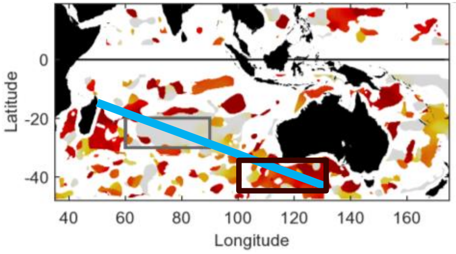
Evidence for a non-westward pathway of eddy (energy) propagation

From our study:

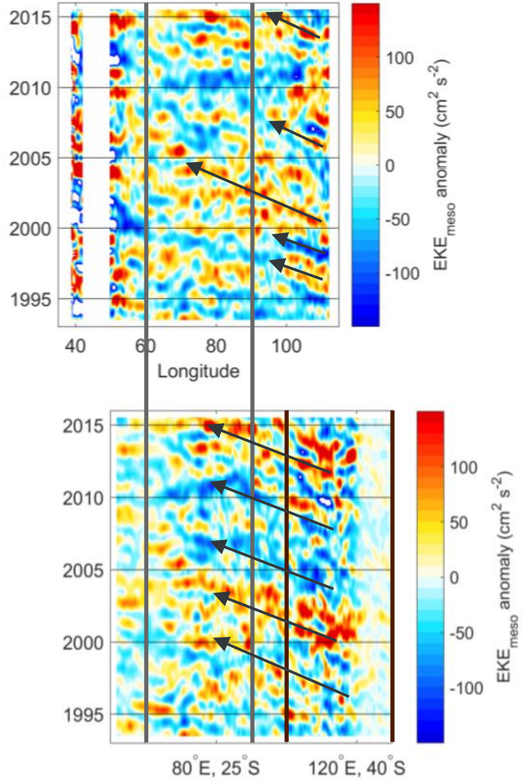
Hovmöller of EKE_{meso} variations along zonal path



Hovmöller of EKE_{meso} variations along “oblique” path



EKE_{meso} anomaly – interannual/decadal frequencies



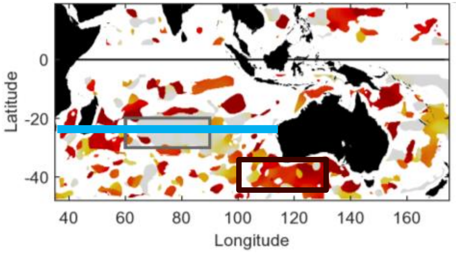
- Crests/troughs of eddy energy seem to propagate further along the oblique path than the zonal path

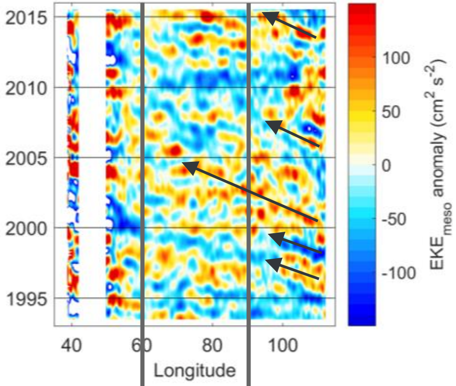
Evidence for a non-westward pathway of eddy (energy) propagation

From our study:

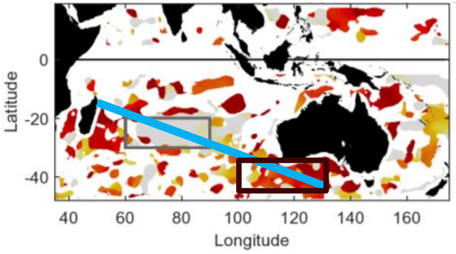
EKE_{meso} anomaly – interannual/decadal frequencies

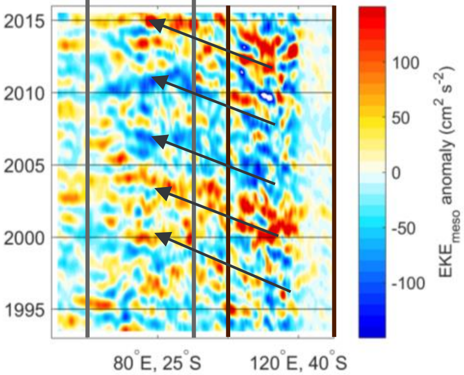
Hovmöller of EKE_{meso} variations along zonal path





Hovmöller of EKE_{meso} variations along "oblique" path





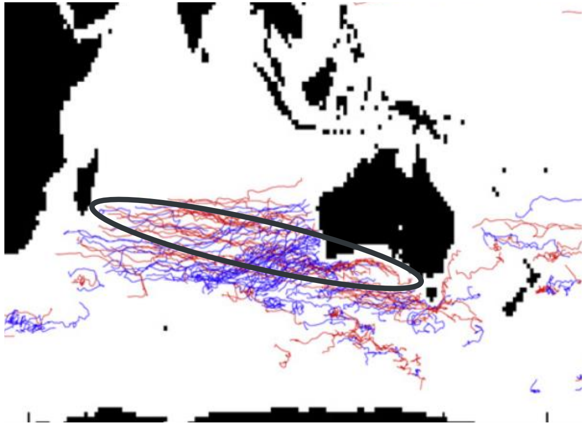
- Crests/troughs of eddy energy seem to propagate further along the oblique path than the zonal path

From Chelton et al. (2011):

Tracks of eddies with lifetimes greater than 2 years

Anticyclonic tracks

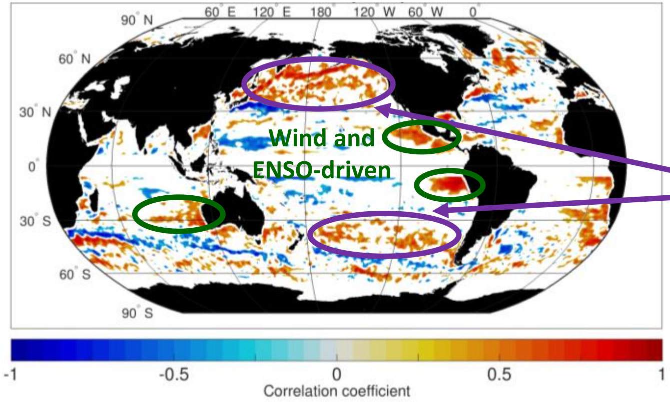
Cyclonic tracks



- Long-lived anticyclonic eddies in this region do propagate along the oblique path, though cyclonic eddies tend to propagate southwestward instead

Future work: how is EKE related to SSH globally?

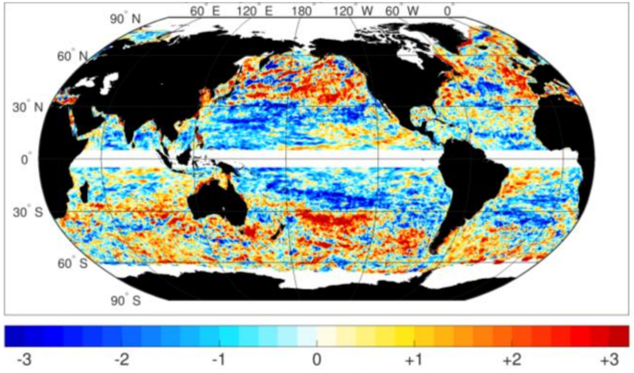
- On a global scale, as sea level is rising, eddy activity also seems to be changing in recognizable geographic patterns



Also locations where EKE trend is positive

SSH-EKE interannual/decadal correlation (detrended), 0 lag

EKE trend (% yr^{-1}), 1993-2016



- The EKE trend map has some resemblance to the SSH-EKE anomaly correlation map (which has been detrended to consist of variations at timescales <24 years)

Conclusions, and future directions

SSIO interannual/decadal eddy variability

- Which mechanism(s) explain the close relationship between SSH and EKE on interannual/decadal timescales in parts of the SSIO?
  - ✓ Tropical Pacific sea level (forced by winds related to ENSO) drives both sea level and mesoscale EKE variations near the Australian coast

- Which climate and/or interior/ocean forcing pathways control the interannual variability of EKE in the SSIO?
  - ✓ ENSO is the primary climate driver of mesoscale eddy generation and variability in the Leeuwin Current region
  - ✓ Further west in the interior ocean, eddy variability is influenced by northwestward propagation of mesoscale energy

Eddy variability in the global oceans

- There is a positive correlation of EKE with SSH at many higher latitude locations
- May be related to the positive long-term trend in EKE at many of these same locations in the satellite altimetry record.

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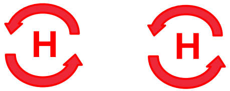
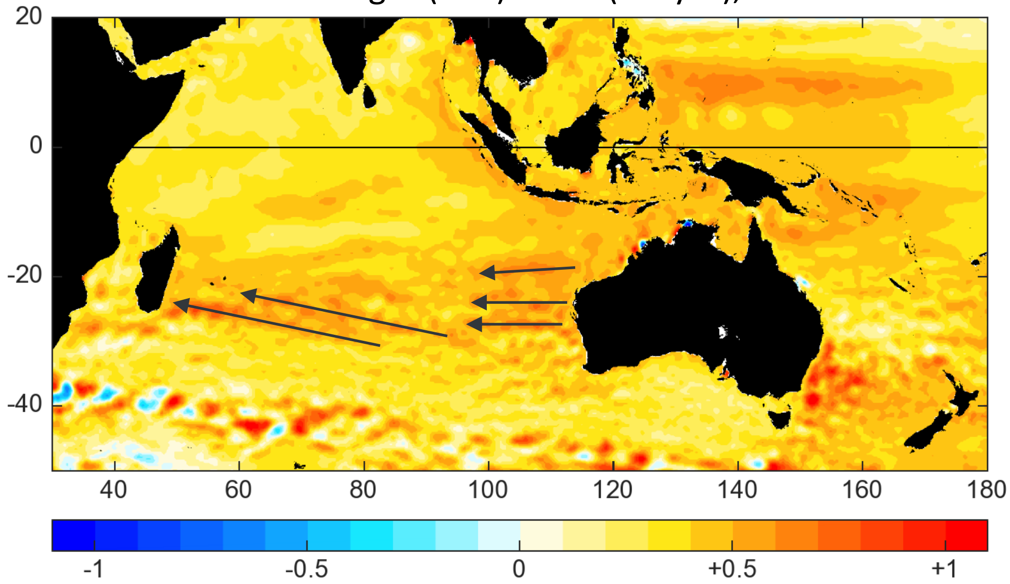
Hypothesis 1: The interannual/decadal variability of EKE in the SSIO is driven by variations in the number of anticyclonic (warm-core) eddies

→ More AC eddies → EKE increases → SSH increases also



Sea surface height (SSH) trend (cm yr^{-1}), 1993-2016



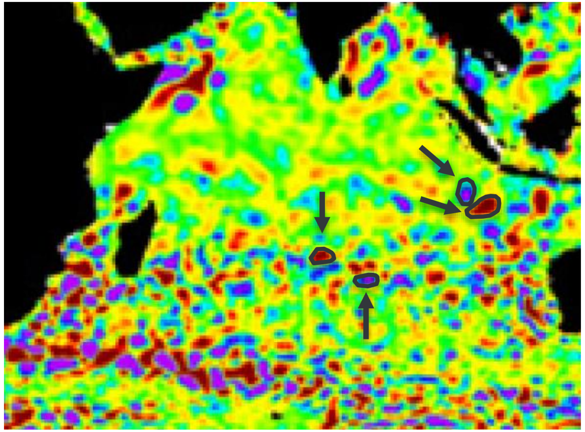
- Highly positive “tracks” in long-term SSH trend look like eddy propagation pathways

Mesoscale eddies and EKE – the eddy counting approach

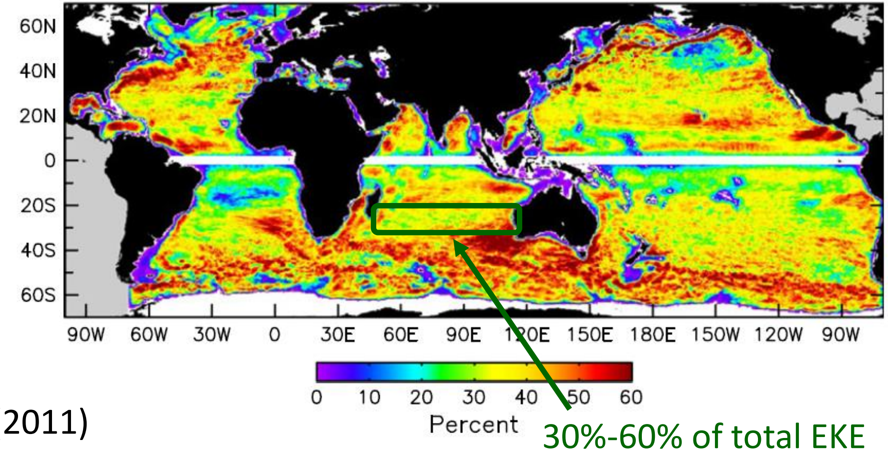
- Isern-Fontanet et al. (2003; 2006), Morrow et al. (2004), and Chelton et al. (2007; 2011) have used algorithms to identify individual mesoscale eddies

- The Chelton et al. (2011) method identifies eddies as closed, compact contours of spatially high-passed sea level anomaly (SSH minus its time mean)

Spatially HP sea level anomaly, 28 Aug. 1996



% of total EKE explained by mesoscale eddies (lifetime ≥4 weeks)

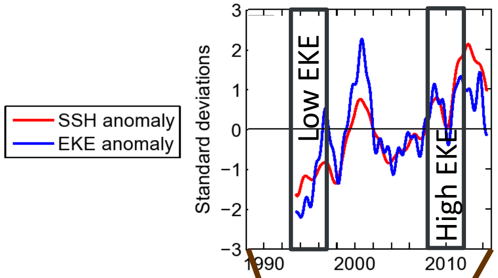


Chelton et al. (2011)

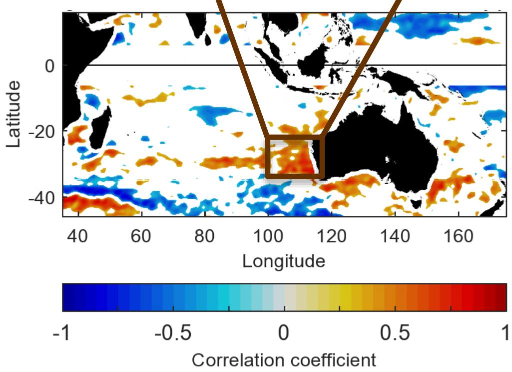
30%-60% of total EKE explained by individual eddies

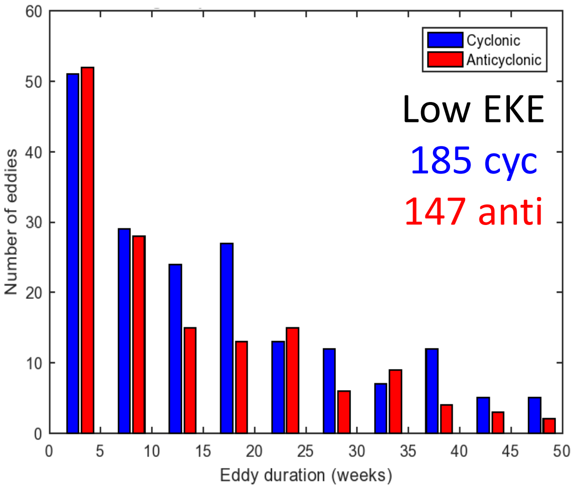
Do anticyclonic eddy variations explain SSH and EKE variability?

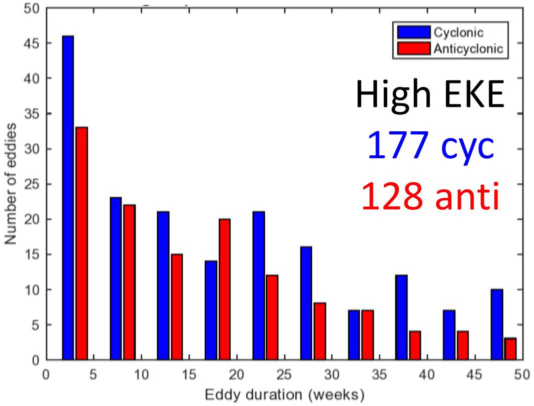
Histograms of cyclonic and anticyclonic eddies identified using the Chelton et al. (2011) method, during low and high EKE periods



SSH-EKE anomaly correlation (after detrending), 0 lag







~~**Hypothesis 1:**~~

~~**More AC eddies → EKE increases → SSH increases also**~~

- There are fewer anticyclonic than cyclonic eddies
- Number of AC eddies does not increase during high EKE & SSH periods